

Higgs-boson production in nucleus-nucleus collisions

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Cross-section calculations are presented for the production of intermediate-mass Higgs bosons produced in ultrarelativistic nucleus-nucleus collisions via two-photon fusion. The calculations are performed in position space using Baur's method for folding together the Weizsäcker-Williams virtual-photon spectra of the two colliding nuclei. It is found that two-photon fusion in nucleus-nucleus collisions is a plausible way of finding intermediate-mass Higgs bosons at the Superconducting Super Collider or the CERN Large Hadron Collider.

The existence of the Higgs boson is one of the most important questions in physics. Of the four known interactions in our Universe, only the electromagnetic and weak interactions have been successfully unified.¹ The exchange particles responsible for the forces are the photon (γ) and the intermediate vector bosons (W^+ , W^- , Z^0) with masses of zero (γ) and 80 GeV (W^+ , W^-) and 91 GeV (Z^0), respectively.² However, in a truly unified theory all exchange particles should have the same mass. The Higgs boson was introduced³ to account for the mass difference between the photon and the intermediate vector bosons via the mechanism of spontaneous symmetry breaking. The discovery of the Higgs boson would therefore provide the last piece of crucial experimental evidence for the unified electroweak theory. However, this theory makes no definite prediction about the mass of the Higgs boson and therefore experimental searches must cover a very large range.

The possible Higgs-boson mass M_H is often classified as light (< 80 GeV), intermediate ($80 \text{ GeV} < M_H < 160$ GeV) or heavy (> 160 GeV). Drees *et al.*⁴ have pointed out that a light Higgs boson can be found at the Large Electron Positron (LEP) collider at the European Center for Nuclear Research (CERN), while a heavy Higgs boson can be found in proton-proton collisions at the future Superconducting Super Collider (SSC) in Texas or at the Large Hadron Collider (LHC), which will be built in the LEP tunnel at CERN. However, intermediate-mass Higgs particles are much more difficult to find.

There have been several recent suggestions⁴⁻⁷ that an intermediate-mass Higgs boson could be discovered by two-photon ($\gamma\gamma$) fusion produced in nucleus-nucleus collisions in the TeV/nucleon energy range. This would be inaccessible for the highest-energy planned nucleus-nucleus collider, which is the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, which will have a beam energy of 100 GeV/nucleon/beam. However, the idea has been suggested⁴⁻⁷ that if one were to accelerate heavy nuclei (instead of only protons) at the LHC or SSC then the beam energies would be 3.4 TeV/nucleon and 8 TeV/nucleon, respectively. The reason for an enhanced cross section is that for nucleus-nucleus collisions the two-photon cross section is larger than that for electron-positron collisions by a factor of Z^4 where Z is the nu-

clear charge.

Given this very exciting possibility it is extremely important to have an accurate estimate of the expected experimental cross section. Three sets of calculations have been made using momentum-space form factors.⁴⁻⁷ As an additional possibility the present work investigates a recent suggestion of Baur⁸ as to how to fold together the Weizsäcker-Williams (WW) virtual-photon spectra⁹ of two colliding nuclei. The advantage of this position space formalism is that one can easily impose the condition that the nuclei do not overlap (otherwise strong interactions occur). For the sake of completeness some of Baur's equations are repeated here. The WW photon spectrum^{8,9} is

$$N(\omega, b) = \frac{Z^2 \alpha}{\pi^2} \left[\frac{\omega}{\gamma v} \right]^2 \left[\frac{c}{v} \right]^2 \left[K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right], \quad (1)$$

where α is the fine-structure constant, ω is the photon frequency, v is the speed of the nucleus, and γ is the usual relativistic factor. K_1 and K_0 are modified Bessel functions and x is defined⁸ as

$$x = \frac{\omega b}{\gamma v}, \quad (2)$$

where b is the impact parameter. For nuclei, there is a minimum value of this impact parameter, below which the $\gamma\gamma$ process will be overtaken by the strong interaction. For the $\gamma\gamma$ process one integrates from this minimum value up to infinity. The $\gamma\gamma$ cross section for two nuclei is obtained by folding the individual $\gamma\gamma$ cross section $\sigma_{\gamma\gamma}(\omega_1, \omega_2)$ with the WW photon spectrum of each nucleus as⁸

$$\sigma = \int \frac{d\omega_1}{\omega_1} \int \frac{d\omega_2}{\omega_2} F(\omega_1, \omega_2) \sigma_{\gamma\gamma}(\omega_1, \omega_2), \quad (3)$$

where the folded spectra are given by⁸

$$F(\omega_1, \omega_2) = 2\pi \int_{R_1}^{\infty} b_1 db_1 \int_{R_2}^{\infty} b_2 db_2 \int_0^{2\pi} d\phi N_1(\omega_1, b_1) N_2(\omega_2, b_2) \times \theta(b - R_1 - R_2), \quad (4)$$

where R_1 and R_2 are the nuclear radii and⁸

$$b^2 = b_1^2 + b_2^2 - 2b_1b_2\cos\phi. \quad (5)$$

The step function θ in Eq. (4) is zero when $b < R_1 + R_2$ and unity for $b > R_1 + R_2$ thus ensuring that the nuclei do not overlap.

The $\gamma\gamma$ reaction cross section for forming the Higgs boson can be related to the two-photon decay width $\Gamma_{H \rightarrow \gamma\gamma}$ as⁷

$$\sigma_{\gamma\gamma}(s) \equiv \frac{8\pi^2}{M_H} \Gamma_{H \rightarrow \gamma\gamma} \delta(s - M_H^2), \quad (6)$$

where s is the square of the invariant mass W^2 :

$$s = W^2 = 4\omega_1\omega_2. \quad (7)$$

An approximate expression for the width is¹⁰

$$\Gamma_{H \rightarrow \gamma\gamma} = 3 \text{ keV} \left[\frac{M_H}{100 \text{ GeV}} \right]^3, \quad (8)$$

but a more accurate expression is¹¹

$$\Gamma_{H \rightarrow \gamma\gamma} = \frac{\alpha^2 G_F M_H^3}{8\pi^3 \sqrt{2}} |I|^2, \quad (9)$$

where G_F is the Fermi coupling constant and $|I|^2$ is calculated according to the formulas of Papageorgiu⁶ but using a W mass of 80 GeV. The use of this more exact expression for the Higgs-boson width gives substantially larger cross sections than one obtains if $|I|^2$ is simply set equal to unity, particularly when the Higgs-boson mass approaches twice the W mass.

The δ function in Eq. (6) is valid in the narrow-resonance approximation. Inserting (6) and (7) into (3), one finally obtains

$$\sigma = \frac{8\pi^2}{M_H^3} \Gamma_{H \rightarrow \gamma\gamma} \int \frac{d\omega_1}{\omega_1} F\left[\omega_1, \frac{M_H^2}{4\omega_1}\right]. \quad (10)$$

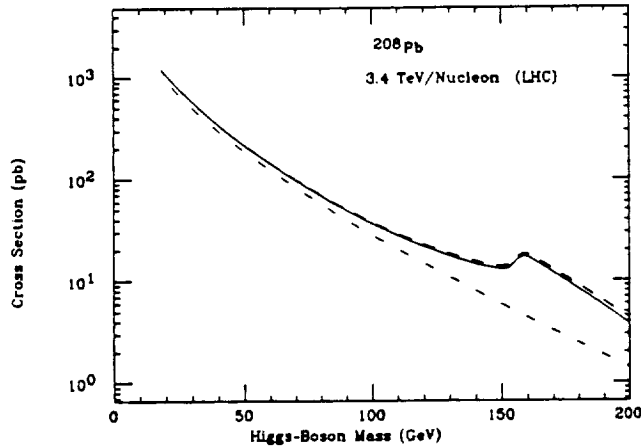


FIG. 1. Cross section in picobarns as a function of mass for Higgs-boson production via two-photon fusion with Pb-Pb collisions at 3.4 TeV/nucleon relevant to the LHC. The dash-dotted curve uses the width of Eq. (8). The solid and dashed curve uses the width of Eq. (9) corresponding to top-quark masses of 100 and 200 GeV, respectively. (These two lines merge together for a Higgs-boson mass of about 100 GeV.)

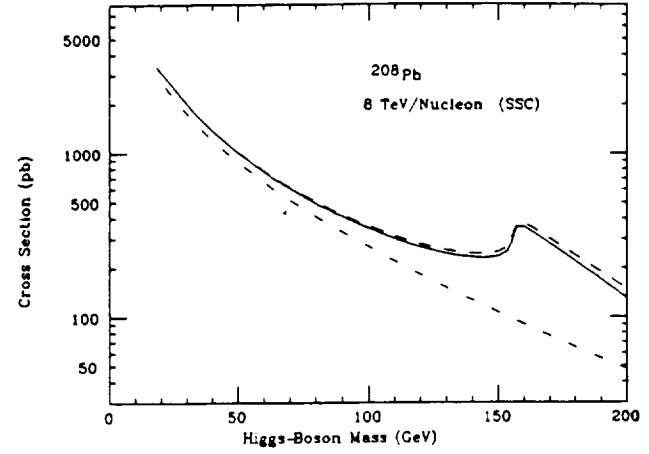


FIG. 2. Same as Fig. 1 except now for 8 TeV/nucleon relevant to the SSC.

Thus one has four nested integrals which must be evaluated numerically.

The numerical procedure can be tested very accurately because if θ is replaced by unity the three integrals in Eq. (4) can be evaluated analytically. Setting θ to unity the above equations were integrated numerically and the number of integration points and maximum energies were chosen so that the numerical answer converged to the analytical answer. These points and energies were then used in the real calculation incorporating the full θ function. (Convergence was again checked.)

The results of the present calculations appear in Figs. 1–4 for top-quark masses of 100 and 200 GeV and for Pb-Pb and U-U collisions at 3.4 TeV/nucleon (LHC) and 8 TeV/nucleon (SSC). One can see that the use of Eq. (9) gives substantially larger cross sections at larger Higgs-boson masses. Note the peak in the cross section when the Higgs-boson mass is twice the W mass, indicating the opening up of a new decay channel.

Recently Cahn and Jackson¹⁰ and Baur and Ferreira Filho¹² have performed similar calculations. In private communications with these authors it appears that we all

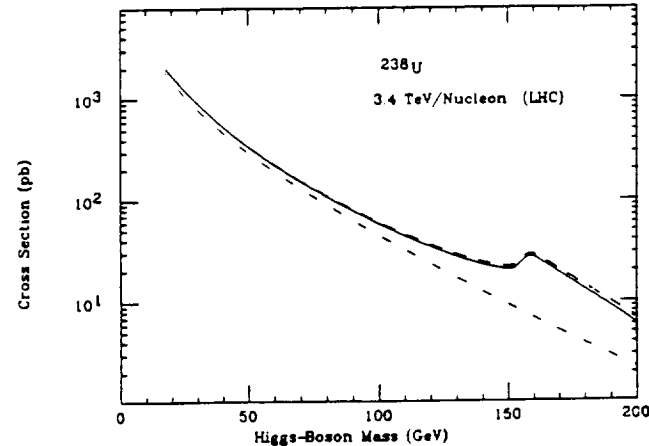


FIG. 3. Same as Fig. 1 except now for U-U collisions.

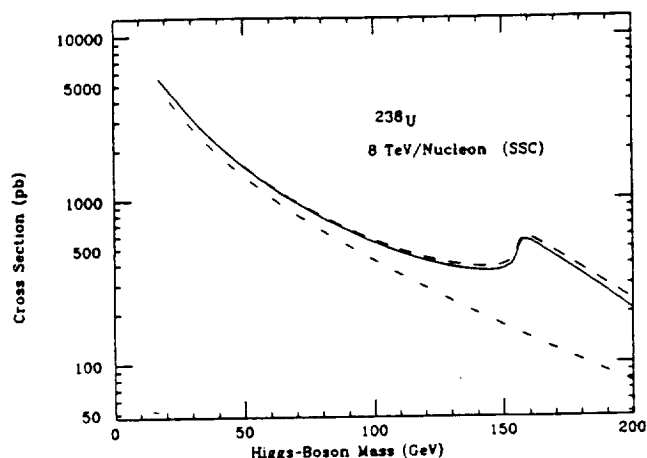


FIG. 4. Same as Fig. 2 except now for U-U collisions.

get the same results if we use the same Higgs-boson two-photon width [Eq. (8)]. However, the calculations presented in Figs. 1–4 now use both widths of Eqs. (8) and (9) above. In addition Wu *et al.*¹³ have also present-

ed calculations based upon the Monte Carlo evaluation of Feynman integrals.

In order to obtain an idea of how the present results compare with those of other authors the results obtained with Eq. (9) are now discussed. For U-U collisions at 8 TeV/nucleon (SSC) and for a Higgs-boson mass of 100 GeV, Grabiak *et al.*⁷ calculate the cross section to be about 800 pb, while Papageorgiu⁶ obtains about 600 pb. The present work obtains about 550 pb (roughly the same for top-quark masses of 100 and 200 GeV). Even though the differences vary as a function of Higgs-boson mass it is clear that the present position-space calculation incorporating a realistic cutoff gives smaller results than previous momentum-space calculations. Nevertheless the cross sections are still quite sizable, particularly for SSC energies, and two-photon fusion via nucleus-nucleus collisions may yet provide a way for discovering intermediate-mass Higgs bosons.

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